Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

Presented at the International Cryogenic Materials Conference, Madison, WI, August 21-24, 1979; also to be published in Advances in Cryogenic Engineering

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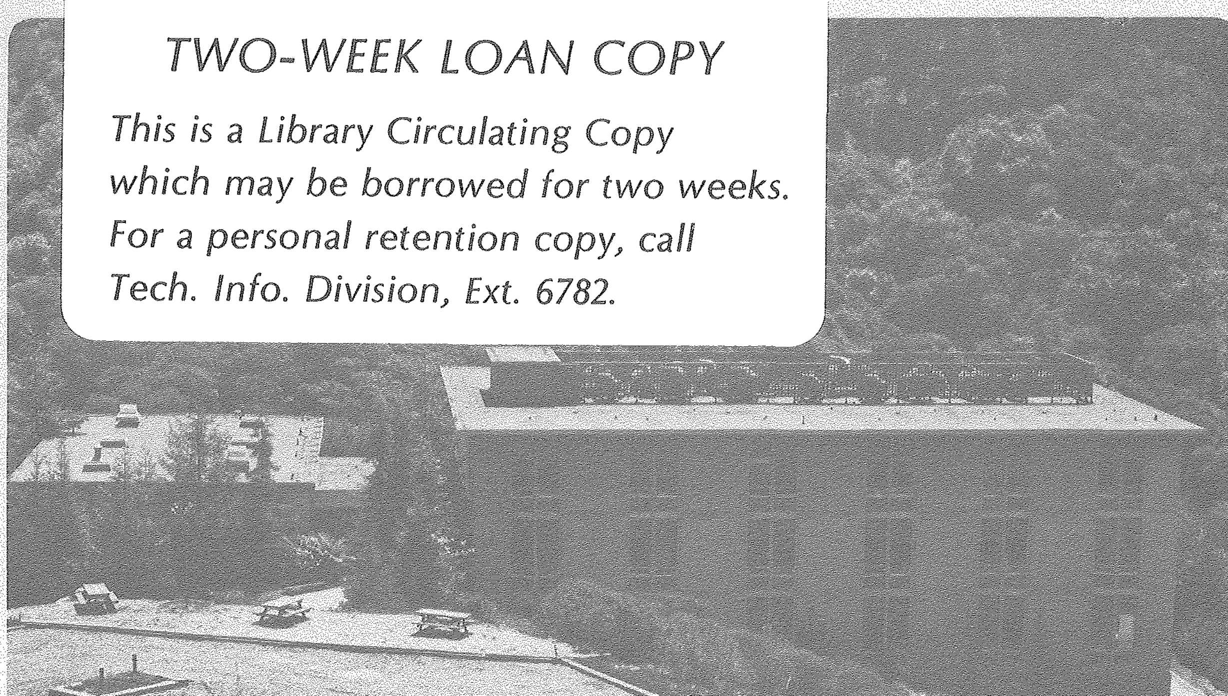
August 1979



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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A REVIEW OF THE DEVELOPMENT OF FERRITIC CONSUMABLES FOR THE WELDING OF 9% NICKEL STEEL: RESEARCH IN THE U.S. AND JAPAN

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INTRODUCTION

Since its development in 1944 by the International Nickel Company, 9% Ni steel has been extensively used for the manufacture of liquified gas containment vessels. Its excellent toughness [1-8], strength[1,2,9], and fatigue[10-12] properties make it suitable for use at temperatures as low as -196°C. Table 1 gives the composition and mechanical properties of a typical quenched and tempered 9% Ni plate (A553 Gr. A). At liquid nitrogen temperature, the tempered martensitic structure of this steel, which contains about 7-10% retained austenite, produces good toughness with mixed mode fracture. Further improvement of the properties of the plate can be obtained by grain refinement procedures[13,14].

However, the excellent properties of this material cannot be utilized to their fullest if it is necessary to join the plates with

(Table 4-1972 N.K.K. G.M.A.W. wire). However, this achievement was rather limited in practical applicability, since weld metal with excellent notch toughness was obtained only under the spary arc conditions, which require a relatively high arc voltage and a large current. Tank fabrication, though, requires the use of the vertical and the horizontal welding positions, for which this type of transfer is unsuitable.

In 1972 the 9NT Committee was set up by the Japan Welding Engineering Society for the purpose of conducting joint research and development aimed at developing practical 9% Ni steel matching ferritic consumables for the MIG welding process[29]. This committee was active for about 15 years but did not necessarily succeed in the development of any particular 9% Ni steel matching ferritic consumable weld wire. However, steel and welding material manufacturers continued research in the same area[30], as shown in Table 4.

Some welding material manufacturers have also been engaged in research on a 9% Ni steel matching ferritic consumable for the submerged arc welding process. In 1970, the Sumitomo Metals Industry[32] in Japan proposed two compositions for submerged arc welding (S.A.W.). Their chemistry and Charpy values are presented in Table 4. However, they do not seem to have succeeded in their attempt as is obvious from the fact that they have not published any experimental evidence.

On the other hand, remarkable progress has recently been made in the mechanization of TIG welding and in the improvement of the semiautomatic TIG welding process. In Japan, for instance, a mechanized TIG welding machine with an automatic voltage controller and an electrode weaving system for all position welding have come into practical use. In TIG welding the intensity and stability of the arc and the filler wire feed rate can be controlled by independent mechanisms. Pure argon gas used in TIG welding to cover the arc and molten pool remarkably inhibits the contamination of the weld metal with oxygen. These advantages of TIG welding significantly facilitated the development of a 9% Ni steel matching ferritic consumable welding. Mention will now be made of several salient features of this TIG welding process[31].

Table 4 gives the chemistry for the 1979 matching G.T.A.W. consumable and Table 5 shows the results of impact tests at 77°K of 9% Ni steel matching ferritic consumable weld metal obtained by an improved semi-automatic TIG arc welding machine which automatically feeds the filler wire into the arc core. The oxygen content of this weld metal was as low as 27 to 33 ppm, providing evidence to indicate the excellent notch toughness of the weld metal.

Further, as the heat input can be easily controlled in TIG welding, the notch toughness of weld metal can be increased through judicious control of welding thermal cycles.

Fig. 1 shows the relationship between notce toughness and welding heat input, as determined in the test welding of a 9% Ni steel plate 12 mm thick. The test specimens were welded with differing heat inputs, followed by bead surface reheating with the TIG arc alone with differing heat inputs. The changes in weld metal notch toughness elicited by bead surface reheating are graphically represented in Fig. 1. As is clear from this figure, the notch toughness of both weld metal and fusion boundary was remarkably increased by surface reheating.

Table 6 shows the relationship between the COD value and welding thermo-hysteresis of the above mentioned weldments. This table also provides evidence to indicate that the COD value can also be remarkably improved by reducing the welding heat input and surface reheating.

The favorable effect of the thermal cycle on the notch toughness of weld metal can also be easily obtained in various ways by simply reducing the welding input heat or by using low heat input in the final pass.

As is evident from the data given above, the weldments obtained by TIG welding exhibit a high degree of notch toughness in the cryogenic temperature range of 77 to 111°K.

Encouraged by these findings, the MFN Committee was set up by the Japan Welding Engineering Society (in January, 1978) in order to undertake a joint research project for establishing practical 9% Ni steel matching ferritic consumable welding by the TIG welding process, and the research project was pursued for about 1.5 years with the participation of universities, government research agencies, electric power and city gas companies as end users of LNG structures, and Nippon Kokan K.K. Part of the results of this research is to be presented as another report before the meeting of this ICMC Conference.

Various experiments were carried out within the framework of this research project concerning the weldability, welding workability, welding defects, and fracture toughness of weldments, and quite satisfactory results were obtained. In the final stage of the research a spherical 9% Ni steel model tank 2 m in diameter and 16 mm in wall thickness was fabricated and pressure tests were performed at the liquefied nitrogen temperature.

All these experiments and tests provided evidence that sufficient fracture toughness of 9% Ni steel matching ferritic consumable weldments could be maintained at cryogenic temperatures down to 77°K[25]. The Japan Welding Engineering Society which reviewed the research reports approved 9% Ni steel matching ferritic consumable welding as suitable for 9% Ni steel.

The above is a brief description of the research and development of 9% Ni steel matching ferritic consumable welding which has been carried on for the past 15 years in Japan.

B. United States.

After A. J. Miller's initial success, a series of welds were made with similar wire compositions obtained from different heats. The tests performed on 1/2 in. (13mm) thick plate were unable to adequately reproduce the previous weld deposit's properties due to problems with hot cracking and remelt porosity[33]. However, work continued and in 1963, I. V. Peck[34] applied for a patent on ferritic consumables in the range of 11.5 to 13.5 wt. % Ni. An optimum composition along the lines of this patent was later reviewed in a 1965 paper by Witherell and Peck[24]. Tables 7a and 7b detail the optimum chemistry and mechanical properties of the 1964 ferritic consumable. During the years of development work on this wire from 1960 to 1963, a number of attempts were made to produce good welds with wire made using standard wire drawing techniques. The presence of adsorbed oxides and plating or pickling residuals on the wire surface severely reduced the toughness of the weld deposit, forcing the researchers to resort to a "shaving" preparation of all wires before welding.

An analysis of the variations in toughness of these modified wires revealed a number of influencing factors. Of prime importance were, of course, the alloying constituents necessary to achieve the required toughness levels. Early in their studies, it was found that additions of molybdenum tended to aggrevate cracking problems during high weld restraint tests. Although this observation conflicted with earlier results obtained with filler metals for the 18% Ni maraging steels[33], it was decided to remove the molybdenum from the composition. Reproduction of the original 132 ft-lb. Charpy impact energy obtained by Miller for the plate casting sample was strongly dependent upon the purity of the melt and the melting practice as well. Assuming that proper control of the wire fabrication was maintained, the actual weld deposit toughness was further influenced by the amount of base metal dilution and the number of weld bead passes used. As the number of weld passes increased for a given thickness, the toughness increased. In addition, a second phase was detected at the dendrite triple points[33]. No studies were made to determine its origin or influence on properties.

In 1975, F. H. Lang[35] patented a modified version of the 1964 12.5% Ni composition. Tables 7a and 7b give the optimum chemistry and mechanical properties determined in this study. As indicated in the Table, the weld deposit was able to achieve more than adequate levels of toughness at -196°C using either the gas tungsten arc welding process (G.T.A.W.) or the gas metal arc welding process (G.M.A.W.). Attempts to use similar wires with the submerged arc welding process (S.A.W.) failed due to the formation of large grains and high residual gas contents. Both factors caused severe reductions in the toughness levels. In general, the effect of microstructure, in particular grain size, was thought to be among the dominant factors controlling low temperature toughness levels for all processes. However, no mention was made in this study about the possibility of embrittling secondary phases, except that the C/Mn ratio was critical in determining the toughness of the deposit. Tests on 2 in. (51mm) thick plate using the electroslag welding process (E.S.W.) produced 25 ft-lb (34J) at -196°C for specimens notched perpendicular to the weld grain growth direction, but less than 5 ft-lb (7J) for specimens notched parallel to the grain growth direction. It is of some interest to note that an ultra-high purity manual G.T.A.W. wire was produced during the study by actually vacuum sucking up samples for wires out of the melt[36]. Tests on these wires showed 160 ft-lb (217J) adsorbed C_v impact energy at 77°K (-196°C) and 105 ft-lb (142J) energy at 4°K.

In 1970, Teledyne-McKay issued a Data Sheet Bulletin[37] to various 9% Ni steel manufacturers and fabricators announcing the availability of a matching ferritic shielded metal arc welding (G.M.A.W.) electrode for 9% Ni steel. The rod was identified as "McKay 9Ni"[38] and had a very basic slag coating of the "XX18" type (low hydrogen, Fe-powder). The electrode's chemistry and mechanical properties are presented in Tables 8a and 8b respectively. Table 8b includes the weld toughnesses reported for various field fabricated plates[39]. For plates under 1/2 in (13mm) in thickness, inadequate toughness levels were produced. This problem was attributed to the insufficient amount of weld pass tempering resulting from the smaller number of beads deposited[39]. This conclusion is in agreement with the INCO evaluations on the need to maximize the number of weld passes. Welding procedures specified for this electrode required minimum delay times of 30 minutes between weld passes followed by a final overnight "bake-out" of the completed weld at 250°F (121°C) to prevent hydrogen cracking. Tables 9a and 9b show the results of Armco Steel's evaluation[40] of the "McKay 9Ni". Weld metal toughness was found adequate but again only if the plate thickness exceeded 1/2 in. (13mm). Due to the general variability of weldment properties with changes in the plate or welding parameters[39], McKay removed the electrode from its commercial electrode line.

In 1977, a research program was set up at the Lawrence Berkeley Laboratory for the purpose of studying the low temperature toughness characteristics of ferritic weld deposits. Our previous experience in the area of ferritic steels had been with the 9% Ni and 12% Ni steels, whose low temperature properties we were able to improve by controlled thermomechanical treatments[13,14]. The approach taken in the welding consumables study was to characterize the microstructural aspects of a variety of G.M.A. welded ferritic weld deposits using advanced analytical techniques, as well as standard evaluation techniques. Since the property of interest was the toughness of the weld at -196°C, most of the testing was carried out using Charpy-V-notch specimens and precracked three-point bend (J-integral) specimens. The primary base plate used for the study was a commercially available A553 Grade A, quenched and tempered 9% Ni steel plate with .010 wt.%S and .012 wt.%P. The four ferritic wire compositions which have been studied to date are presented in Table 10. The first two compositions, designated 778-5, and 778-6, are based, respectively, on the 1977 G.T.A.W. wire composition proposed by I. Watanabe[25] and the 1975 G.M.A.W. wire composition patented by F. Lang[35].

The weldment fabricated with the Japanese composition, 778-5, originally designed for G.T.A.W., was evaluated for G.M.A.W. using a special low sulphur (.002 wt.%), low phosphorus (.003 wt.%) base plate, in order to better correlate the results with those obtained by Watanabe with the G.T.A.W. process. As anticipated on the basis of the lack of sufficient deoxidant levels in the 778-5 wire, the radiographic quality of the weld was poor, exhibiting rejectable porosity defects over 80% of the weld length. However, there were some defect free regions which allowed us to extract impact toughness specimen from the weld metal, fusion zone and heat affected zone. The test results showed that the weld metal was capable of absorbing 120 ft-lb. (163J) impact energy at -196°C in defect-free regions; the fusion zone had a slightly lower impact energy of 100 ft-lb. (136J) at this temperature.

In comparison, the weldment fabricated using the 778-6 wire and the standard (higher S,P) base plate produced poor impact properties in the weld metal with a C_v value of 20 ft-lb. (27J) at -196°C. The fusion zone, on the other hand, exhibited an increased toughness relative to the weld of about 37 ft-lb. (50J) at this temperature. The carbon and silicon levels in this composition were higher than in 778-5 and could have contributed to the reduced toughness. Scanning electron microscope pictures revealed the presence of complex silicon-manganese oxides on the fracture surface surrounded by microcracks.

The preliminary data obtained from the early evaluations of these two weldments, as well as data on the effect of various elements on ferritic weld toughness levels[41], led us to propose a number of new compositions for study. Of these, two have been analyzed. Their chemistries are indicated in Table 10 under "Mo-Modified 11Ni", otherwise referred to as "789-1", and "LCMM-1". The more satisfactory of the two consumables is the molybdenum modified 11Ni wire. Test results for the toughness properties of the weldments fabricated using this wire and the standard base plate are indicated in Table 11. Note that at -196°C, which was the test temperature for all specimen, the weld metal is capable of achieving 40 ft-lb. (54J) impact energy and 125 ksi-$\sqrt{in}$ based on the "J-integral" method of fracture toughness evaluation. One of the important features of the fabrication of this weldment was the use of 15 face and 1 root pass in a 5/8 in. (16 mm) thick plate. This produced considerable tempering and grain refinement of the weld deposit as shown in Figs. 2(a) and (d). The fracture mode associated with the highly grain refined regions [Fig. 2(a) - (c)] was a microvoid coalescence process, which occurred preferentially along the interdendritic regions, as was discovered by analyzing Figs. 2(b) and (c) in the "fiber-like" region indicated by the arrow. In coarser grained regions, the percent of brittle cleavage fracture increased. Analysis of the weldment with Mossbauer backscattering techniques revealed no retained austenite in the weld deposit. Preliminary data on the surface chemistry of these cleavage areas, obtained by using a scanning Auger microprobe, was insufficient. A more detailed discussion of the microstructural aspects of the fracture path as a function of ferritic deposit chemistry or phase is detailed in another report presented at this ICMC Conference[42]. Further microstructural studies using transmission electron microscopy and the scanning Auger microprobe are scheduled for the coming months and should provide more information than is currently available on the toughness behaviour of these ferritic weld deposits at low temperatures.

CONCLUSION

The purpose of this review was to collate the results and knowledge obtained from the various research and development programs on ferritic consumables for 9% Ni steel in order to provide future investigators with a more concise data basis for their experimentation than was currently available. From the research discussed in this paper, it appears evident that it is possible to develop good low toughness properties in 9% Ni matching ferritic consumables under certain conditions. How limiting these conditions are, or whether or not the welding metallurgist can resolve them, will depend upon the results obtained from the basic analytical studies currently being conducted in both Japan and the United States. A lot of progress has been made since 1960 and continued research in this area is recommended.

ACKNOWLEDGMENT

The authors would like to acknowledge the contributions provided by the Armco Research Lab, C. E. Witherell, and F. H. Lang in their discussions with the authors on the various aspects of this development work.

The preparation of this review and portions of the research cited here were supported by the Office of Materials Science, Division of Basic Energy Sciences, U.S. Department of Energy under Contract W-7405-ENG-48.

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Table 1: Armco Steel's A553 Grade A Plate

CHEMICAL COMPOSITION:

FE	NI	C	MN	SI	P	S	H	O	N
Bal.	9.18	.068	.49	.22	.012	.010	2ppm	10ppm	10ppm

MECHANICAL PROPERTIES:

ORIENTATION & TEMPERATURE		Y.S. ksi (MPa)	T.S. ksi (MPa)	ELONG. (%)	R.A. (%)	C_V ft-lb (J)
25°C	L	102 (703)	113 (779)	29	73	115 (156)
	T	102 (703)	112 (772)	28	71	66 (90)
-196°C	L	137 (945)	170 (1172)	29	66	69 (94)
	T	136 (938)	169 (1165)	29	58	41 (56)

Table 2: Austenitic Consumables for 9% Ni Steel

* S.M.A.W. ELECTRODES
  - 70Ni/15Cr/Fe
  - 50Ni/13Cr/Fe/Mo
  - 16Cr/13Ni/Mn/W: MODIFIED AUSTENITIC

* S.A.W. WIRES
  - 67Ni/27Mo
  - 67Ni/20Cr/3Mn
  - MATRIXED STIFFENED Ni-Cr WIRE
  - 35Ni/16Mo/BAL. Fe TUBULAR WIRE
  - 57Ni/16Cr/16Mo/3W

* G.M.A.W. WIRES
  - Ni-Cr (67Ni/18Cr)
  - Ni-Cr-Ti (67Ni/15Cr/2.5Ti)
  - Ni-Cr-Mo (BAL. Ni/20Cr/9Mo)
  - MODIFIED AUSTENITE (25Cr/20Ni)

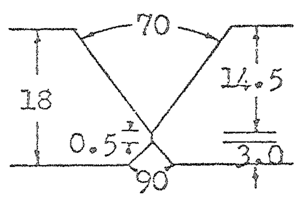
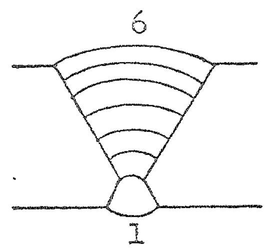
Table 3: Mechanical Properties of the Austenitic Consumables

PROCESS	TYPE OF ELECTRODE	T.S. ksi (MPa)	Y.S. ksi (MPa)	C_v ft-lb (J)
S.M.A.W.	High Ni/Cr (70Ni-15Cr)	85(590)-95(660	50(340)-60(414)	25(34)-55(75)
	Modified Austenitic (13Ni-17Cr)	85(586)-105(740)	64(441)-71(490)	20(27)-41(55)
G.M.A.W. & S.A.W.	High Ni/Cr (60-70Ni; 16-20Cr; up to 9Mo)	90(621)-119(821)	57(393)-79(545)	50(68)-81(110)

Table 4: Japanese Ferritic Consumables for 9% Ni Steel

PROCESS	DEVELOPER	Ni	C	Mn	Si	Ti	Co	C_v (-196°C) ft-lb (J)
S.M.A.W.	1966 (N.K.K.)	10.3	.023	.46	.25	----	1.37	10 - 17 (14 - 24)
G.M.A.W.	1972 (N.K.K.)	8.8	.024	.59	.07	----	----	11 - 40 (15 - 54)
	1974 (Sumitomo)	10.3	.034	.58	.10	----	----	40 (54)
		11.4	.028	.52	.028	----	----	66 (90)
S.A.W.	1970 (Sumitomo)	11.0	.027	.28	.06	----	----	32.5 (44)
		8.7	.05	.43	.16	----	----	29 (40)
G.T.A.W.	1974 (Kobe)	10.9	.024	.37	.02	.035	.43	140 (191)
	1977* (N.K.K.)	11.1	.02	.27	tr	----	----	112 (152)
	1979 (N.K.K.)	11.05	.04	.39	.01	.01	.34	53 - 155 (72 - 210)
				(7 ppm Boron)				

Table 5: Results of Charpy-V impact test***

Welding Condition**	Edge Preparation	Pass Schedule	Gas Flow Rate* (l/min)	Oxygen Content in Weld Metal (ppm)	vE_{77K} (Joule)
Welding Current 230 A Welding Speed 40-90 mm/min			10	31	78
			12.5	27	166
			15	33	172
			20	30	136

* Shielding Gas: Pure Argon

** Semi-automatic Welding Machine: Chemetron Corporation, TC-1

*** Matching Ferritic Filler Wire: 0.04C-0.01Si-0.39Mn-11.0Ni (1.2mmφ)

Table 6: Results of 3-point bending COD test** (Weldments 12mm in thickness)

Heat Input (KJ/mm)	Surface Reheating (KJ/mm)	Testing Temp. (K)	Notch Positions	Critical COD* (mm)
17	As Welded	111	Weld Metal	0.428
			Fusion Boundary	0.405
	10	111	Weld Metal	0.608
			Fusion Boundary	0.601
26	As Welded	111	Weld Metal	0.448
			Fusion Boundary	0.251
	10	111	Weld Metal	0.240
			Fusion Boundary	0.226
	17	111	Weld Metal	0.524
			Fusion Boundary	0.525
33	As Welded	111	Weld Metal	0.102
			Fusion Boundary	0.127
	10	111	Weld Metal	0.129
			Fusion Boundary	0.108
	17	111	Weld Metal	0.420
			Fusion Boundary	0.357
	26	111	Weld Metal	0.416
			Fusion Boundary	0.465

* Test: BSI DD-19 (Fatigued notch)

** Matching Ferritic Filler Wire: 0.04C-0.01Si-0.39Mn-11.0Ni (1.2mmφ)

Table 7: Ferritic Gas Shielded Arc Filler Wires Developed at INCO

OPTIMUM WIRE CHEMISTRY (WT.%)

DATE	Fe	Ni	Mn	C	Si	Ti	Al	S & P
1964	Bal.	12.5	.65	.05	.01	.05	.02	.005
1975	Bal.	11.0	.20	.05	.10	.05	.03	.005

MECHANICAL PROPERTIES

PROCESS	Min. T.S. ksi (MPa)	Min. Y.S. ksi (MPa)	C_V (-196°C) [ft-lb (J)] As-Welded	Stress-Relieved
1964 G.M.A.W.	115 (793)	100 (690)	40 (54)	56 (76)
1975 G.T.A.W.	----	----	80 (109)	
G.M.A.W.	----	----	40 (54)	

Table 8: "McKay 9Ni" Covered Electrode Developed by Teledyne-McKay

CHEMISTRY:

Ni	C	Mn	Si
10.75	0.06	0.25	0.35

MECHANICAL PROPERTIES

T.S. ksi (MPa)	Y.S. ksi (MPa)	ELONGATION %	R.A. %
128 (883)	118 (814)	19	62

	LAB.	FIELD			
C_V (-196°C) ft-lb (J)	37 (50)	5-10 (7-14)	14-18 (19-24)	32-40 (43-54)	36 (49)
Plate, t (in.)		1/4	3/8	5/8	3/4

Table 9: Armco Steel's Evaluation of "McKay 9Ni" in 5/8 in. Plate

TENSILE (-171°C)

T.S. ksi (MPa)	Y.S. ksi (MPa)	ELONGATION %	R.A. %
122 (827)	111 (765)	20	----

TOUGHNESS (-196°C)

NOTCH LOCATION	C_V ft-lb (J)	LAT. EXP. (mils)	%SHEAR
WELD METAL	27 (37)	18	95
H.A.Z.	45 (61)	23	80
BASE METAL (A353)	43 (58)	31	100

Table 10: Chemical Compositions of the Ferritic Gas Shielded Arc Wires (L.B.L.)

ALLOY	Fe	Ni	C	Mn	Mo	Si	Ti	Al	O
778-5	Bal.	11.06	.023	.22	----	----	----	----	40ppm
778-6	Bal.	10.98	.056	.20	----	.14	.05	.04	130ppm
Mo-Mod.* 11Ni	Bal.	11.5	.054	.24	.33	----	.07	.02	10ppm
LCMM-1	Bal.	12.25	.02	.34	.32	----	.03	.04	20ppm

* Nitrogen Level after Swaging: 100ppm
Hydrogen Level " " : 30ppm

Table 11: Charpy-V-Notch and 3-Point Bend Fracture Toughness Test Results for the Mo-Modified 11Ni Weldment

REGION	C_v ft.-lbs.	Lat.Exp. mils	K_{1C}^{EE} ksi-in$^{1/2}$	K_{1C}^{J} ksi-in$^{1/2}$	C.O.D. mils
WELD METAL - Molybdenum modified composition 786-1	39.9	25.5	162.7	125.3	3.0
FUSION ZONE	63.0	30.5	194	156.4	4.9

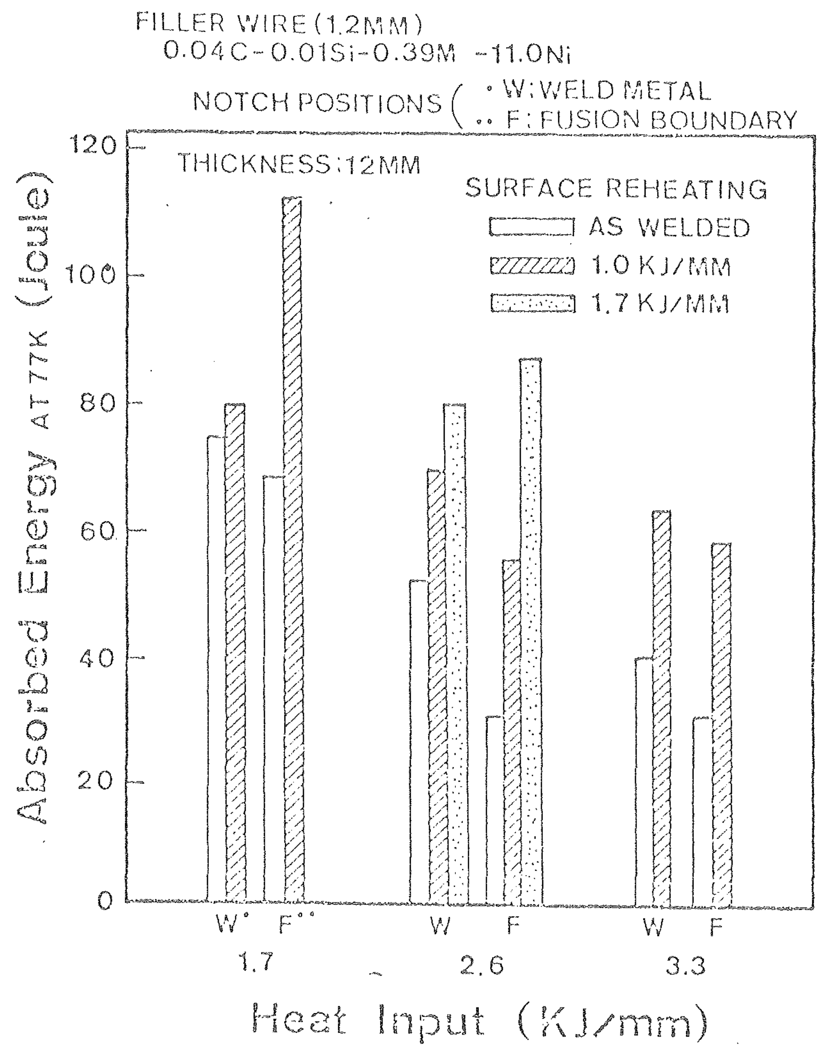


Figure 1. Relationship between welding heat input and the notch toughness of weldments; improvement by surface reheating

FRACTURE MODE vs. WELD MICROSTRUCTURE (-196°C)

(Mo - Modified 11-Ni Filler Wire)

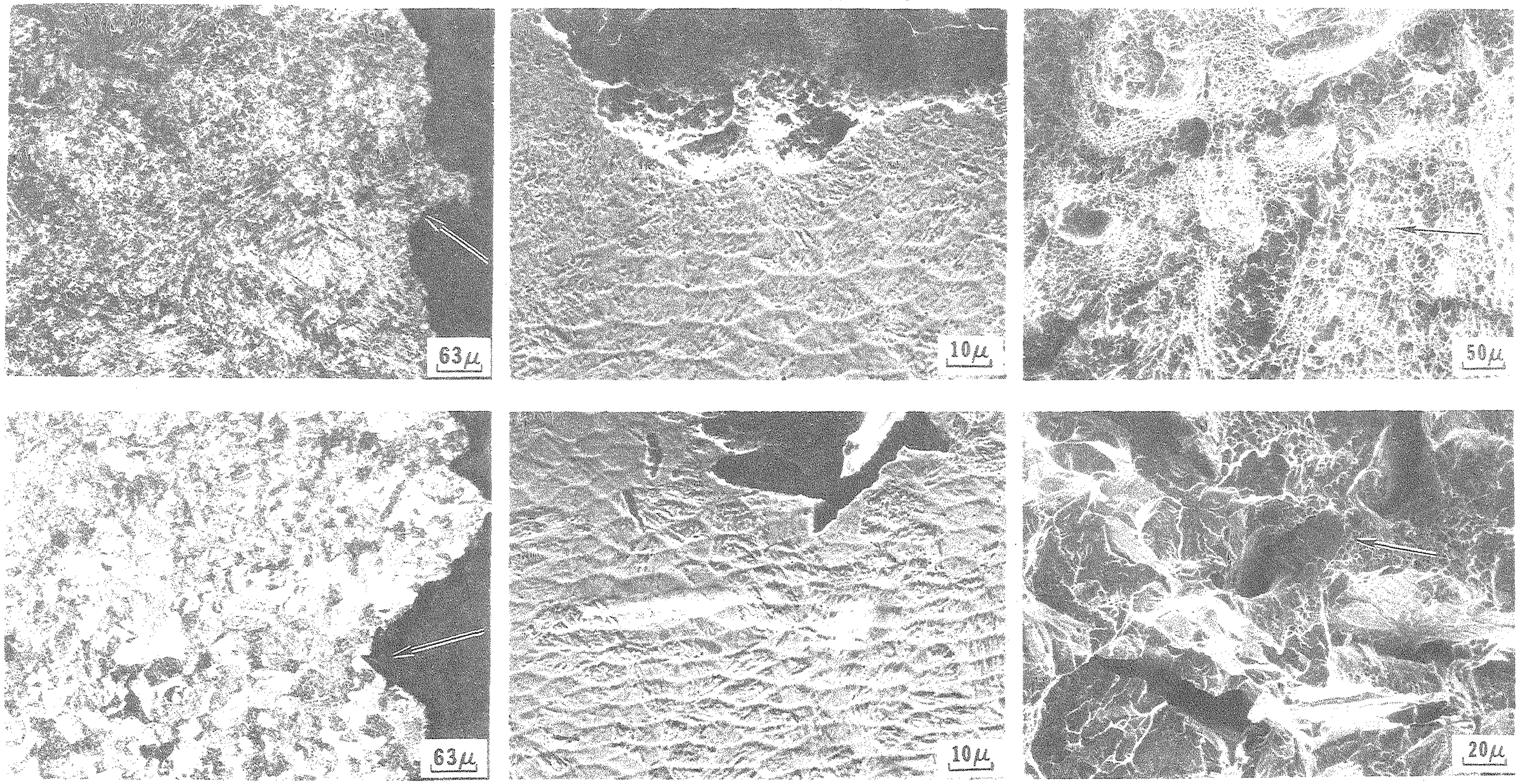


Figure 2.

XBB 798 10353